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Research article

Spatio-temporal dynamics of groundwater storage changes in the Yellow River Basin

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ABSTRACT

Groundwater is an important source of water supply and ecosystem resilience. However, limited information on spatio-temporal dynamics makes a complete assessment of available groundwater resources difficult, impairing sustainable water management. The Gravity Recovery and Climate Experiment mission (GRACE) has recently made this possible. In this study, we used the Yellow River Basin (YRB) as a model system to explore the use of spatio-temporal dynamics information about groundwater change derived from the GRACE datasets for regional groundwater management. While there was an overall decreasing trend ($R^2 = 0.57$) during the last 14 year, the groundwater storage over the whole basin decreased significantly ($p < 0.0001$, slope changed from −0.0137 cm/month to −0.0684 cm/month) since 2010 (2010–2016) and showed stronger fluctuations than the time before (2003–2009). The range and the standard deviation of groundwater storage change also increased in recent years especially after 2010. At the basin scale, locations which exhibited higher variabilities (large standard deviation) over time generally showed radical decrease of groundwater storage. The results indicated that groundwater depletion may reduce the aquifers' function for ecosystem resilience, thus posing risks to the ecosystem of the YRB and threatening its people to climate change and extreme events. Despite the overall trend, the changes were heterogeneous if looking at finer scales: spatially, there was a gradual decline of storage from west to east (e.g. the change in December 2016 was −3.6, −9.1 and −25.8 cm for the upper, middle and lower reach, respectively); and temporally, the timeseries among the reaches were significantly different ($p = 0.023$). Our hotspot analysis also indicated the heterogeneity in groundwater decline across the basin and through the time. Additionally, it showed that human factors (e.g. groundwater consumption) become dominant in determining the groundwater change pattern over climatic variations. We therefore call for more attention to groundwater in developing sustainable water management strategies and suggest a closer cooperation of neighboring provinces in the YRB to have a reciprocal strategic plan for water regulation, protection, and management.

1. Introduction

Groundwater is the primary reserve of freshwater available for human use (USGS, 2016). It acts as an underground reservoir for surface water bodies such as wetlands, lakes and rivers and serves the needs of > 2 billion people for drinking water and irrigation (Alley et al., 2002; USGS, 2016). Due to slow responses to the cycles of rainfall and drought than surface water, it serves as a buffer, providing extra water when surface waters dry up or extra space to store water when precipitation is excessive, thus enhancing ecological resilience (Robins and Fergusson, 2014; Rockström et al., 2014). Despite its importance, groundwater has received less attention in scientific research and management than surface water (Sanford et al., 2006; Jha et al., 2007). Lack of accurate measures of available groundwater in any locations (Gleeson et al., 2016) and its spatial and temporal changes adds on to the challenge in studying and managing groundwater (Unland et al., 2013). Without this information, it is difficult to determine the capacity of groundwater resources, and to draft appropriate management plans.

The limited understanding about the spatio-temporal dynamics of groundwater results from both the intrinsic features of groundwater as well as a lack of research investment (Sanford et al., 2006). Groundwater has traditionally been more difficult to measure and monitor than surface water, due to the cost and difficulty in drilling monitoring wells (Ireson et al., 2006; Gleeson et al., 2016). Groundwater has a complex recharge-discharge system making accurate and spatially explicit monitoring difficult. In addition, the complexity and fluctuations from

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the seasonal recharges from the precipitation and river runoff make the temporal monitoring more challenging (Chang et al., 2017). However, improved understanding of changes in groundwater storage across space and through time is critical for improving water management (Alley et al., 2002).

With the launch of NASA's Gravity Recovery and Climate Experiment mission (GRACE) in 2002, groundwater changes can now be monitored with less human labor over a large area using the twin satellite (Bhanja et al., 2017). Researchers have demonstrated its promising application in monitoring groundwater at the global (Wada et al., 2010; Famiglietti, 2014; Richey et al., 2015) as well as at the regional scales (Rodell et al., 2007; Voss et al., 2013). For example, Rodell et al. (2007) identified a significant depletion of groundwater storage in northwestern India at a mean rate of 4.0 ± 1.0 cm/yr equivalent height of water using the GRACE. More recently, Rodell et al. (2018) used the GRACE data to quantify the terrestrial water storage in 34 regions around the globe and identified 7 regions among them that have significantly lost freshwater storage in the past 14 years (March 2002 ~ April 2016) mainly due to groundwater depletion. Other studies demonstrated the accuracy of using GRACE to measure groundwater change. For instance, Landerer and Swenson (2012) suggested that basin-scale gain factor as well as the grid-point gain factor can reduce the Root Mean Square Difference of the unscaled estimates to within 20% or less in regions like Huai River Basin, a tributary of the Yellow River. Huang et al. (2015) reported that the groundwater storage anomalies estimated from GRACE data (2003–2013) was in well agreement with those estimated from *in situ* observations (2005–2010) for both the Piedmont Plain ($R^2 = 0.91$) and East Central Plain ($R^2 = 0.75$) in North China. They have also proved that the GRACE data could detect changes in both shallow and deep groundwater layers.

Despite the opportunity of quantifying spatio-temporal dynamics of groundwater change using available data from the GRACE, current studies have not yet deliberately discussed the implication of groundwater changes for improving water management. Most GRACE-based groundwater studies generally summarized main aquifers around the world and compare groundwater change with precipitation, evapotranspiration or other hydraulic parameters individually (Alley et al., 2018; Khaki et al., 2018; Ndehedehe et al., 2018). Few of these studies presented some connections with management: i.e. discussed the changes based on management units, analyzed the reasons of changes with regards to both human and natural factors, or explored the implications of groundwater change for sustainable water management (Giordano et al., 2004). However, usually the water management practices are implemented through administratively-defined regions (e.g. provinces), and the water stress usually results from the synergetic effects of both human and nature (Rodell et al., 2018). Nevertheless, the upstream-downstream conflicts remain one of the barriers for sustainable management (Ray and Bijarnia, 2006; Voss et al., 2013).

While previous studies using GRACE have explored the regional groundwater changes in various river basins around the world including Mississippi River Basin (USA) (Rodell et al., 2007), Colorado River Basin (USA) (Castle et al., 2014), Canning Basin (Australia) (Munier et al., 2012), Congo basin (Africa) (Ndehedehe et al., 2018), there is seldom thorough assessment of groundwater storage changes in Yellow River Basin (YRB) of northern China (Richey et al., 2015). The YRB is one of the most important basins around the world covering nine provinces (in part or full) in China and nourishes > 120 million peoples. Groundwater is a valuable resource in this region, not only serving as an increasingly important water supply for drinking and irrigation, but also as a mitigating agent that alleviates extreme events of drought and flood (Yu, 2002; Nie et al., 2015; Craddock et al., 2010; Varis et al., 2014). The average groundwater extraction is more than 13.2 billion m^3 per year, accounting for 26% of the total water use in the region (Giordano et al., 2004). Unfortunately, recent years have witnessed signs of groundwater stress, including reduced river base flow, declines of well levels, and land subsidence (Cai and Rosegrant, 2004; Liu and Xia, 2004). Therefore, it is imperative to examine the groundwater changes in the YRB to ensure sustainable development for the whole basin. The water management in the YRB is overseen by the Yellow River Conservancy Commission (YRCC), and detailed administrative policies are adjusted and implemented province-wise. Therefore, apart from basin level studies, it is necessary to examine the spatio-temporal dynamics at provincial level to provide clear suggestions for each management unit. At the same time, the YRB are usually divided into three reaches (upper, middle and lower reaches) differing in topography, landscapes, climates, and land uses (Yu, 2002; Liu and Di, 2007). These heterogeneities in topology and geography also lead to distinct socio-economic conditions among reaches. Therefore, it is possible that the synergetic effects of human and natural factors will be different among these reaches. With this regard, it is also important to examine the spatio-temporal dynamics of groundwater in the YRB at the reach level.

The objectives of this study are to employ GRACE satellite-based groundwater change data to quantify spatio-temporal dynamics at multiple spatial scales (basin, reach and provincial scales) in the YRB between 2003 and 2016 to better understand patterns in groundwater storage change and explore their implications for regional water management.

2. Study area and data

2.1. Yellow River Basin

The YRB (0–4800 m), located in the north of China, is one of the largest river basins in the world, with an estimated recharge area of 795,000 km^2 (Fig. 1). Based on topographical variations (high west and

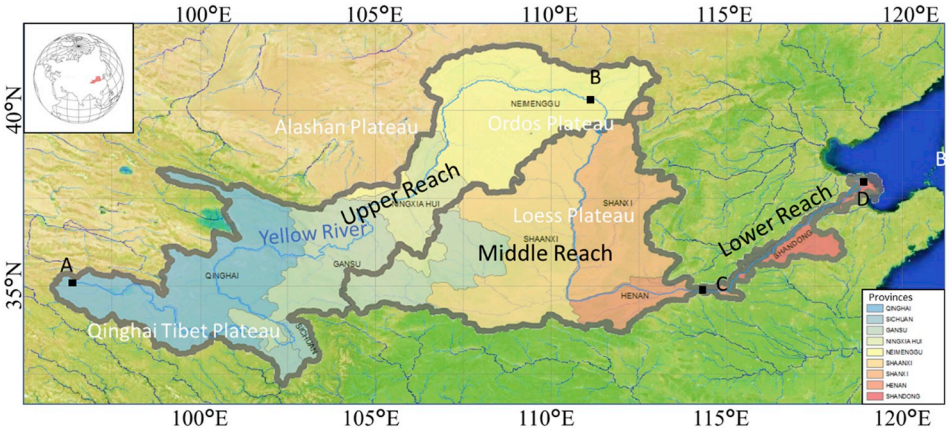

Fig. 1. Yellow River Basin, the study area. The bold lines delineate three reaches (upper, middle and lower reach). The colored polygons represent nine provinces in the YRB. The blue curves represent the flow accumulation across the basin. The main flow path of the Yellow River is boldfaced by a continuous blue curve from Qinghai Tibet Plateau passing Alashan Plateau, Ordos Plateau and Loess Plateau, and ultimately meeting th Bohai Sea. Point A, B, C and D are the key points of the Yellow River: AB is the upstream, BC is the middle stream, and CD is the downstream (revised from Gassert et al., 2013). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

low east), it is commonly divided into three reaches: upper, middle and lower reaches (Yu, 2002; Liu and Di, 2007). From an altitude around 4800 m at the source in Tibet-Plateau (Point A in Fig. 1), it descends to 1000 m at Hekou County (B), 400 m at Zhengzhou City (C), ultimately flowing to Bohai Sea (D) (Fig. 1). The upper reach receives water from melted glacier on the Qinghai Tibet Plateau. Because of the high disparities in altitude from the upper reach to middle reach, the latter suffers from high water erosion with infertile lands in the loess plateau and ordos plateau. The lower reach consists of alluvial plains, which are good for growing crops, and therefore features high population density and dense urban areas compared with reaches upstream. However, lower reach suffers from flood events the most.

There are nine provinces along the river – Qinghai, Sichuan, Gansu, Ningxia Hui (or Ningxia), Shaanxi, Neimenggu, Shanxi, Henan, and Shandong (Fig. 1). The river currently nourishes more than 120 million people (12 percent of China's population), waters more than 200,000 km^2 arable land (15 percent of China's farmland), generates nearly 8 trillion yuan per year (14 percent of China's GDP), and is an important cultural and historical icon (Hays, 2013; Yellow River Conservancy Commission of MWR, 2016).

2.2. Data sources

Terrestrial water storage is the summation of water storage in different compartments, including groundwater, soil moisture, surface water, snow, and ice. We used the Terrestrial Water Equivalence (unit:cm) extracted from the GRACE RL-05 monthly grid data (Level 3) to represent the Terrestrial Water Storage (TWS). The data is available at http://grace.jpl.nasa.gov and supported by the NASA MEASUREs Program (Swenson, 2012; Landerer and Swenson, 2012; Swenson and Wahr, 2006). Matlab program was developed to extract the data within the YRB from Jan. 2003 to Dec. 2016. For the missing data in some months due to technical issues such as battery management (see http://grace.jpl.nasa.gov/data/grace-months/), we interpolated the data using linear interpolation based on the neighboring months.

We obtained the remaining water compartments in the terrestrial water storage (apart from the groundwater) from GLDAS_NOAH10_M.001 (Rodell and Beaudoing, 2007), which includes a series of land surface parameters simulated from the Noah 2.7.1 model in the Global Land Data Assimilation System (GLDAS). This monthly dataset is in 1.0° resolution and ranges from 1979 to the present. It was acquired as part of the mission of NASA's Earth Science Division and archived and distributed by the Goddard Earth Sciences Data and Information Services Center (GESDIC: https://disc.gsfc.nasa.gov). Despite other options, we chose the variables including Plant Canopy Surface water, Average Soil Moisture and Accumulated Snow from GLDAS representing changes of Surface Water Storage (△SWS), Soil Moisture (△SM) and Snow Water Equivalence (△SWE), respectively following Rodell et al. (2004). Groundwater Storage change (△GWS) was then calculated with the equation as below (Rodell et al., 2007; Voss et al., 2013):

$$\triangle GWS = \triangle TWS - \triangle SWE - \triangle SM - \triangle SWS \quad (1)$$

All the data are anomalies relative to the Jan. 2004–Dec. 2009 time-mean baseline. To be noticed, the GWS value derived from GRACE dataset is in the unit of cm, which is the mass change of groundwater storage represented by the equivalent water height. Readers should therefore take caution that it has a different magnitude and a different meaning from locally measured groundwater table change.

To indicate the reliability that reader could expect from GRACE-based groundwater surveys with regards to the possible measurement and leakage errors of the satellite signals, we mapped out the total error of the GRACE data (Landerer and Swenson, 2012). Further improvements for the data accuracy have also been proposed (see section 4). We estimated the errors using the following equation:

$$\sigma_G = \sqrt{\sigma_M{}^2 + \sigma_L{}^2} \quad (2)$$

where σ_M is the measurement error and σ_L is the leakage error.

2.3. Data processing

For all the variables listed in Equation (1), the spatial resolution is 1° × 1° and temporal resolution is month. For each variable in calculation, we first downloaded a rectangle extent (96.5E ~ 118.5E, 32.5N–41.5N) with the time range from Jan. 2003 to Dec. 2016. Then we imported them into the ArcGIS (ESRI Inc.) and used Image Analysis to 'clip' the extent according to the irregular boundaries of the polygons in the YRB. This boundary feature layer of the YRB was obtained from Gassert et al. (2013). We then recorded the coordinates of all the grid centroids within the boundary and used MATLAB (Mathworks Inc.) to extract all the variables into Microsoft Office Excel (Microsoft Inc.) for further analysis.

We also used grid-point gain factor to reduce the error of signal attenuation in filtered GRACE time series. It is a scaling parameter derived in minimizing the misfit between the unfiltered and filtered timeseries of the monthly mean GLDAS water storage estimates (Landerer and Swenson, 2012). Since gain factors are dimensionless, the gain-corrected time series is just the arithmetic product of the TWE and gain factor. The MATLAB program for processing GRACE data including the coordinates of grid centroids in the YRB was developed accordingly.

Then, we examined groundwater timeseries in multiple spatio-temporal scales (basin, reach and provincial level) to understand groundwater dynamics in the YRB. Spatially, we averaged the 1° × 1° grid data at basin, reach and provincial level respectively. We also found that provinces in the similar geological locations (from west, middle to east) have similar range of groundwater changes and often exhibited similar pattern of the changing trend. We therefore presented them in three groups. Temporally, we averaged monthly timeseries at the whole study period (Jan. 2003–Dec. 2016) level and at annual level. We adopted linear regression analysis to estimate the trend of groundwater decrease and used ANOVA analysis to testify the mean difference between different regions in SPSS (IBM Inc.) (Quirk, 2012). To provide more direct information for management, we further categorized the values of groundwater changes. The thresholds were determined based on the range of values for all the grids in the YRB and the indication of impacts in the real life (Zhen and Routray, 2002). Detailed categorization is listed in Table 1.

Finally, we conducted Anselin Local Moran's I cluster and outlier analysis to find the hotspots of groundwater decline (Anselin, 1995). The cluster maps indicate whether a spatial clustering is more pronounced than one would expect in a random distribution. It is to identify groups of statistically significant decreases/increases of groundwater based on value and distance instead of human-defined boundaries like provinces or reaches. In this way, we could find out the scale for proper way of analyzing groundwater situation and developing management strategies.

Table 1
Categorization of water table and its indication.

Thresholds of Water Table/cm	Indication of groundwater change
< -10	Severe decline
−10 ~ -5	Minor decrease
−5 ~ 5	Normal fluctuation
5–10	Minor increase
> 10	Abnormal increase

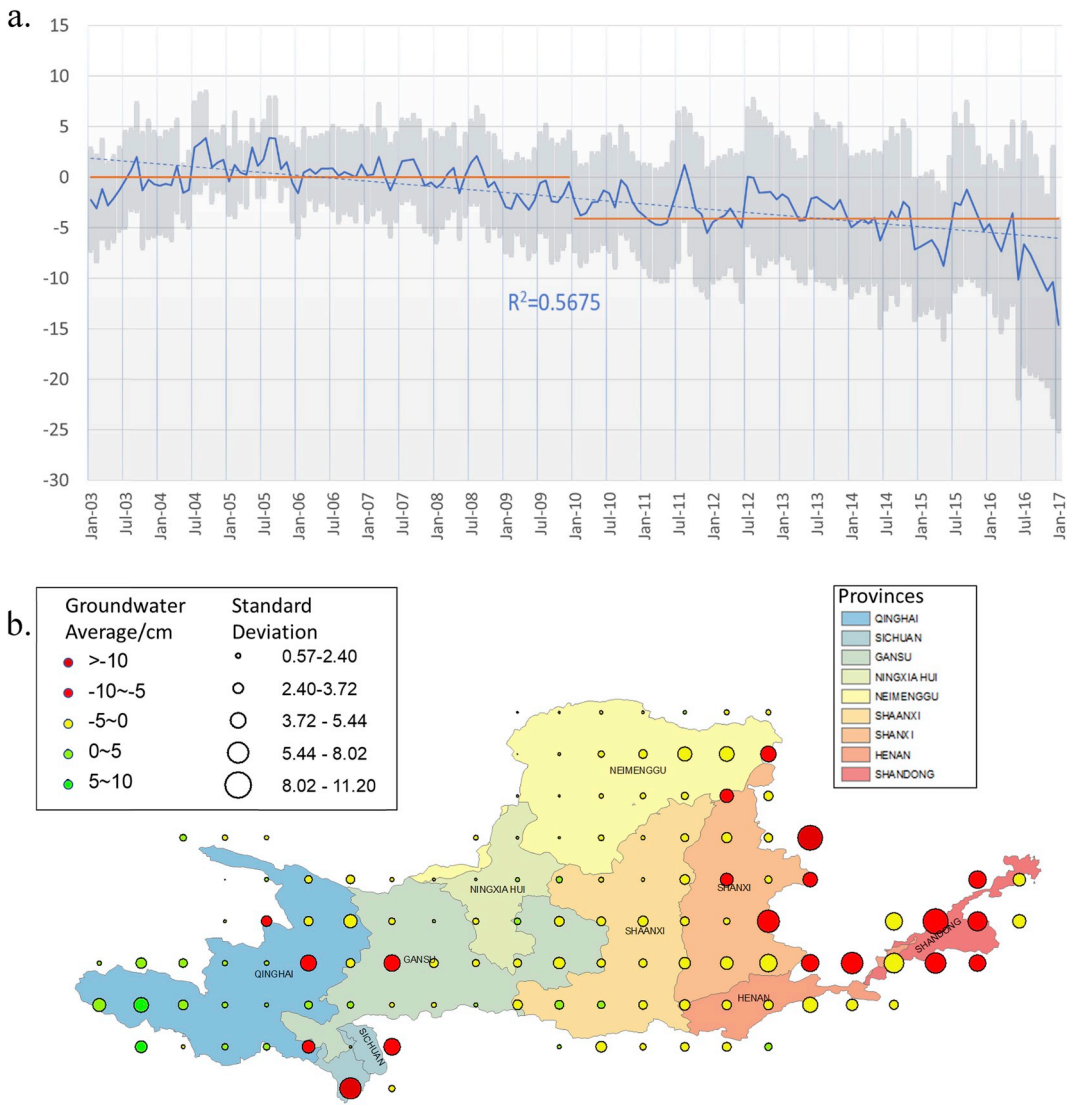

Fig. 2. Spatial and temporal averaged groundwater storage in the YRB. a) The monthly time series displays the spatially-averaged groundwater storage changes over time in the YRB (unit: cm). The shaded area shows one spatial standard deviation of the mean groundwater storage change in the YRB, suggesting that the spread-out of the values in grids changed over time. Two orange lines represent the arithmetic mean before and after 2010 (0.02 cm and −4.01 cm) respectively. The blue dotted curve represents the linear fitting for the whole study period. b) The point colors (red and yellow ones are the decrease from the baseline and green is the increase from the baseline) represent the change of the averaged groundwater storage in each grid from 2003 to 2016. The point size represents one temporal standard deviation for each grid measuring temporal fluctuations of the groundwater storage in each grid from 2003 to 2016. We included all the grids that the YRB covers, even if it just covers a fraction of the grid. The points, which are the centroids of these grids, therefore sometimes being outside of the YRB boundary. Provinces in the YRB from west to east are sequentially colored from blue, yellow, to red. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

3. Results

3.1. Spatio-temporal changes of groundwater in the YRB

Spatio-temporal changes measured at basin, reach and provincial level generally showed decrease of groundwater storage over the study period (2003–2016). This was more pronounced after 2010. We observed a general trend: the locations with high fluctuations were usually the places with severe declines of groundwater storage. Groundwater patterns showed apparent differences in various geographical regions and have shown shifted hotspots of groundwater decline among these regions since 2010.

3.1.1. Spatio-temporal variability at the basin level

Across the entire YRB basin, there were annual fluctuations, with groundwater storage typically at a relative maximum around August and relative minimum in May (Fig. 2a). According to a linear regression ($R^2 = 0.5675$), groundwater decreased gradually over the 14 years. According to t test, the mean groundwater storage in the first half of the study period (Jan. 2003–Dec.2009) was significantly higher than the second half of the study period (Jan. 2010–Dec. 2016) ($p < 0.0001$). The annual minimum groundwater storage in April 2011 was lower than any of the months between 2003 and 2011, and this record within study period was again broken in 2012, 2014, 2015, and 2016, and reached −14.64 cm in Jan. 2017. The slope of the fitting curve became more steeply negative after 2010 (from −0.0137 cm/month to −0.0684 cm/month), indicating that groundwater has been decreasing at an accelerating rate since 2010.

The standard deviation exhibited an increasing trend especially in recent years (2010–2016) indicating that the groundwater changes in grids across the YRB showed more spatial differences over time (Fig. 2a). Additionally, the range (maximum-minimum) of annual

fluctuations in the average groundwater storage in the YRB has increased over the study period, especially after 2010 (Fig. 2a). While groundwater storage in the YRB typically had several waves of drop and rise before reaching the annual maximum or minimum in each year, fluctuations became simpler after 2010. The storage decreased or increased directly to the annual minimum and maximum with fewer intermediate fluctuations.

Spatially, the groundwater storage showed the longitudinal zonation (Fig. 2b). In the west where river source locates, the average groundwater storage during 2003–2016 increased compared with baseline values during 2004–2009. A stripe of minor-severe groundwater decline was observed around the border between Qinghai and Gansu (Fig. 2b, Table 1). In the middle of the YRB, the groundwater storage exhibited normal to minimal fluctuations. In the east, there was another vertical zone of minor-severe groundwater decline. Generally, the average groundwater storage gradually declined from west to east. The places with higher variances of groundwater storage are usually the areas with more groundwater declines. Specifically, the southeastern part showed more obvious groundwater decreases than other parts of the YRB, and, at the same time, higher fluctuations than other areas.

3.1.2. Spatio-temporal variability at the reach level

When analyzing the annual groundwater storage in each reach, we found that the mean groundwater storage changes over the study period (2003–2016) were different among the three reaches of the Yellow River Basin (Fig. 3a, $p = 0.023$). Generally, the groundwater storage change in upper reach was relatively higher than the middle reach while the groundwater storage change in lower reach was much lower than the middle reach (Fig. 3b).

When taking a closer look at the monthly change, we found that the upper and middle reach had more consistent fluctuation while the lower reach exhibited an opposite pattern (Fig. 3c). In the upper and middle reach, groundwater storage were relatively high in summer (~July) and relatively low in winter (~January). However, the lower reach showed opposite pattern, in which groundwater storage dropped in summer (~July) and returned in winter (~January).

There was a tipping point in 2010 when all the three reaches continuously exhibited negative values which indicated that the groundwater storage were continuously lower than that of 2004–2009 baseline level. Before 2010, the groundwater tables in three reaches generally showed normal fluctuation to minor changes (−10–10 cm). After 2010, the declining trend of groundwater storage were more obvious, with the annual minimum values continuously broke the record-low within the study period. Also, as the value of annual groundwater minimum in the lower reach was always closer to the *previous* annual groundwater minimum in the rest two reaches, it implies that the groundwater changes in the lower reach were affected by upstream and had a time lag against the two reaches upstream (Fig. 3c).

The most recent two years (2015–2016) witnessed the most severe signs of groundwater depletion in the YRB especially in the lower reach (Fig. 4c). The upper reach started to show minor declines in these two years whereas the middle reach started to show severe declines (Fig. 4a and b). The lower reach displayed astonishing decreases and signs of depletion: severe declines continued to emerge from 2010 till most recent 2016 when all the months throughout the year presented severe declines. Overall, the lower reach had the most months with severe groundwater declines compared with the other two reaches during 2003–2016 (Fig. 4d). At the same time, the lower reach had more months with abnormal increases (> 10 cm). It implies that the lower reach fluctuates more abruptly and may have a more vulnerable ecosystem.

3.1.3. Spatio-temporal variability at the provincial level

Provinces along the Yellow River from upstream to downstream are respectively Qinghai, Sichuan, Gansu, Ningxiahui, Neimenggu, Shaanxi, Shanxi, Hennan, and Shandong. Among them, Ningxia, Shaanxi and Shanxi are mostly covered by the YRB (Fig. 5a).

At annual scale, all the provinces in the YRB showed obvious and continuous decreases of groundwater storage since 2009 except for Qinghai province (Fig. 5b). Before 2009, groundwater changes were within 5 cm, while after 2009, Sichuan, Shandong, Henan, Shanxi, Shaanxi and Neimenggu successively showed apparent decreases (< -5 cm). Shandong provinces reached record-low in the last year of the study period (2016), indicating an emerging sign of severe groundwater decline. Despite general decreases in other provinces in the second half of the study period (2010–2016), Qinghai province was an exception: its annual groundwater storage showed apparent increase in 2012 with subsequent gradually decreases thereafter.

At the monthly scale, provinces exhibited different patterns between the first (2003–2009) and second half (2010–2016) of the study period. Before 2009, groundwater storage in all the provinces exhibited normal fluctuations (-5 cm ~ 5 cm) except for Shandong province. After 2009, the annual range (maximum-minimum) of groundwater storage in each group was expanding, especially the lower boundary (annual minimum) (Fig. 5c, d and e).

Qinghai, Gansu and Sichuan presented consistent and normal fluctuations before 2009, while they showed different patterns in the second half of study period (2010–2016): Qinghai showed higher annual maximum (> 5 cm) than before, Gansu showed lower annual minimum (< -5 cm) than before, and Sichuan showed even lower annual minimum (< -10 cm) than the first half period (2003–2009) (Fig. 5c).

Ningxiahui, Neimenggu, and Shaanxi exhibited consistent and minor fluctuations (−5 cm ~ 5 cm) before 2009, while they showed general decrease of groundwater storage after 2009: Their annual maximum was around baseline (0 cm), while their annual minimum were lower than −5 cm (Fig. 5d).

Henan and Shanxi had minor fluctuations (−10 cm–10 cm) around baseline (0 cm) before 2009, whereas they showed increasing slope of downward trend after 2009, indicating that these two provinces were depleting groundwater storage in recent years and at an increasingly rapid rate. Shandong province exhibited abrupt changes throughout the study period (2003–2016), but apparently showed decreasing trend after 2009. The annual minimum in Shandong was reached as low as −35 cm in 2016 (Fig. 5e).

3.2. Hotspots of groundwater decline from 2003 to 2016 in the YRB

There was a high heterogeneity in hotspots of groundwater decline across the basin and through the time (Fig. 6). Generally, there was a shifted pattern of the hotspots between the two halfs of the study period. In earlier years (2003–2009), the hotspots of annual groundwater decrease often located in the upper reach (in Qinghai and Gansu) and the cluster of annual groundwater increase located in the middle reach (in Shaanxi and Shanxi). Contrarily, in later years (2010–2016), hotspots of groundwater declines concentrated in the middle and lower reaches (Neimenggu, Shaanxi, Shanxi, Henan and Shandong) whereas the groundwater increases clustered in the upper reach (mostly Qinghai) (Fig. 6).

There were some abnormal years that require a closer look. In the first half of the study period (2003–2009), 2003 and 2004 witnessed relatively different patterns against other years. In these two years, there were hotspots of groundwater increase in the intersection of Qinghai and Gansu provinces, and hotspots of groundwater decrease in Shaanxi province. The pattern showed a sign of latitudinal zonation which led to more groundwater in the south and less groundwater in the north. In the latter half of the study period (2010–2016), 2011 is a special year, when most of groundwater decreases concentrated in Gansu, while groundwater storage increased both in upstream (Qinghai) and downstream (Ningxia and Neimenggu).

Even though abnormal points appeared randomly across the basin and through the time, there were some points that continuously showed

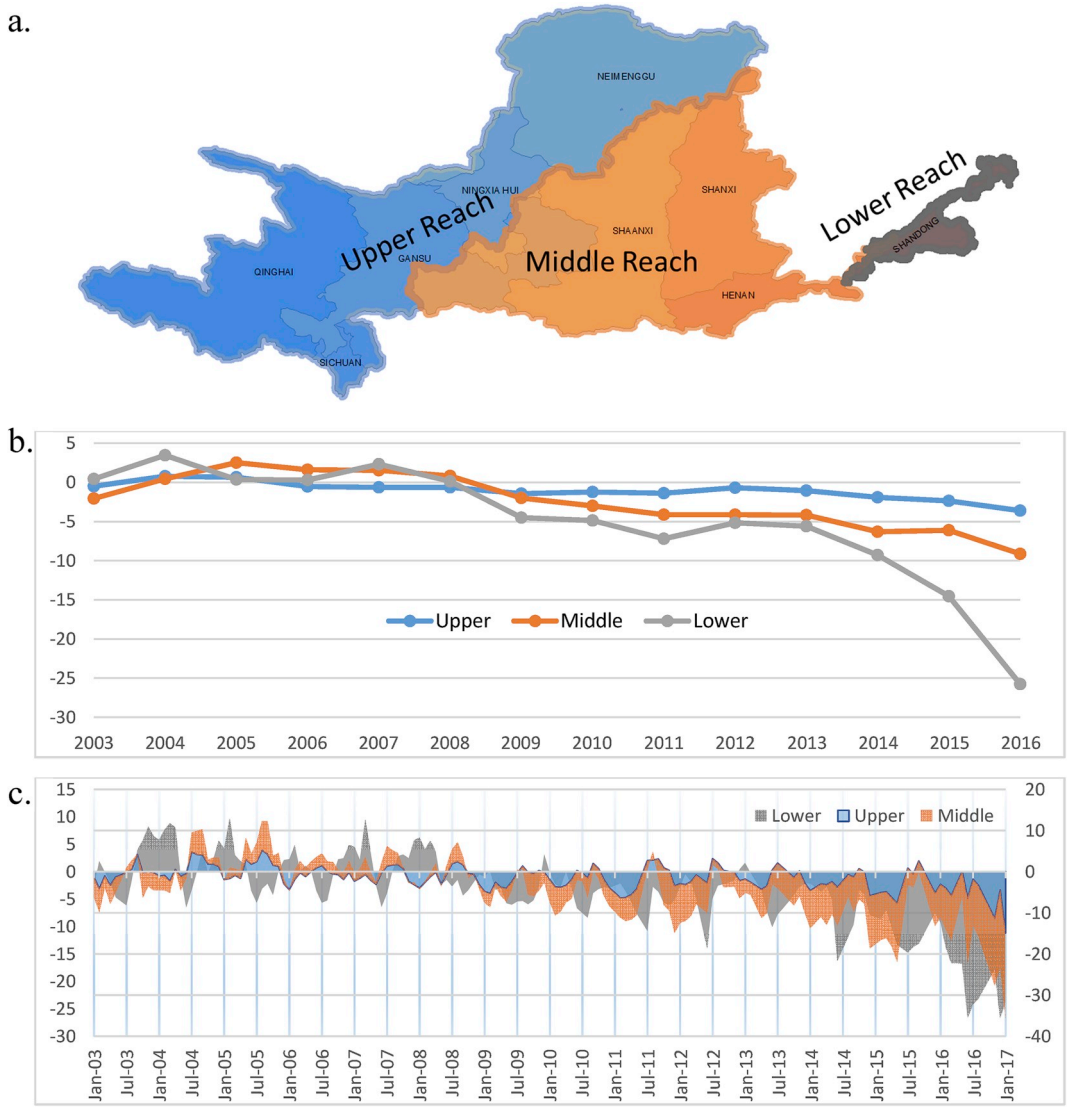

Fig. 3. Annual and monthly time series of groundwater storage changes in the three reaches (unit: cm). a) The coverage of upper, middle and lower reaches. Blue indicates the upper reach, yellow the middle reach, and gray, the lower reach. b) The annual time series of groundwater storage for each reach. c) The monthly time series of groundwater storage for each reach. Y axis represents groundwater storage of each reach compared with 2004–2009 baseline values. The lower reach follows the y axis on the right [20, −40], while the upper and middle reaches follow the scale on the left [15, −30]. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

abnormal high groundwater storage: the points along the intersection between Qinghai and Gansu provinces, as well as the point in the northeastern of Shanxi Province. These points require further investigation to understand potential reasons. There was also abnormal low groundwater storage in the intersection of Henan and Shandong from 2006 to 2008, but later disappeared. It may be related to same historical events during that three years. To be noticed, some abnormal points were connected with clusters. For example, some abnormal high groundwater storages were among groundwater decrease clusters, while the abnormal low groundwater storages were near groundwater increase clusters. In these cases, the abnormal points imply the disconnection of groundwater flow with surrounding aquifers.

4. Discussion

Overall, our results demonstrated that remote sensing data (GRACE), along with data assimilation products (GLDAS) can provide detailed and spatio-temporally explicit information for regional understanding of groundwater storage changes. Temporally, the general decrease of groundwater storage especially after 2010 indicated that the balance of the recharge-discharge system of the aquifers in the YRB was broken. Groundwater depletion in the YRB in recent years (2010–2016) was consistent across different spatial scales (basin, reach and province). Spatially, the hotspots of groundwater decline have shifted from the west to the east over our study period. After 2010, apart from the source region (Qinghai province) which showed signs of groundwater increase, the rest of the provinces displayed accelerated declines of groundwater storage. The lower reach had the most severe groundwater declines especially in the last two years (2015–2016), as well as the highest fluctuations. This emerging sign of decline severity implies a deteriorated situation of groundwater storage in the lower reach that needs special attentions.

At the basin scale, we observed a general decreasing trend in groundwater storage from 2003 to 2016, which testifies a trend of groundwater depletion that was implied by other ground-based monitoring data (Liu and Xia, 2004). Also, the high fluctuations in groundwater changes were always found in the places where the groundwater storage was low, which indicates that, with low water

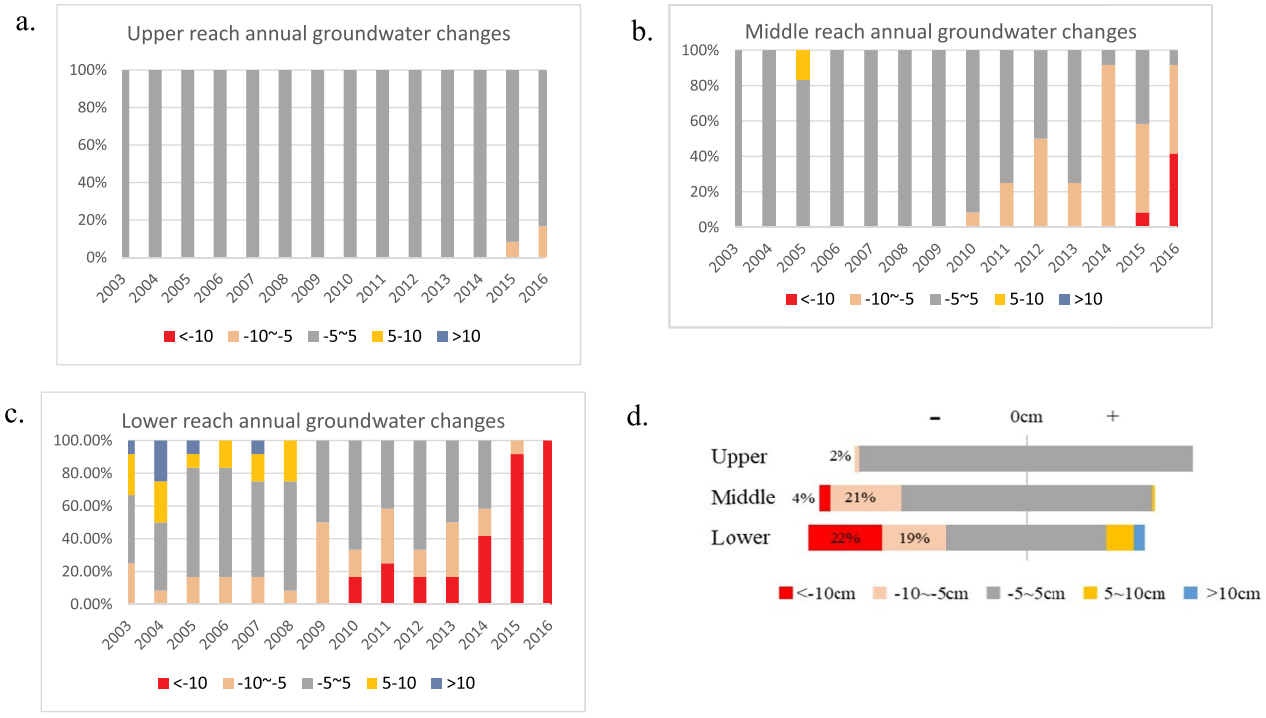

Fig. 4. Decline severity of monthly groundwater in three reaches of the YRB from Jan. 2003 to Dec. 2016. Groundwater change values are categorized into five levels (Table 1) to examine the severity of the groundwater change, especially the groundwater decline. Vertical bar graphs show the percentage of months in each year with various levels of groundwater changes in a) upper reach b) middle reach & c) lower reach. d) Months in same categories are summed up from 2003 to 2016 to see the overall pattern in each reach. For the ease of comparison, the bars align along the 0 cm line represents the middle of the gray bar in each reach. The bars on the left of the line represent the months with groundwater decline while the parts on the right indicate the months with groundwater increase.

storage, the aquifer system is more unstable, thus leading to a more vulnerable ecosystem. It implies that the area with low groundwater storage has relatively quicker processes of recharge and discharge than other places. Compared with natural discharge to lakes and rivers, the relatively direct way that groundwater leaves from the aquifers is through human extraction (Bernadez et al., 1993). Different from natural recharge from precipitation and river runoff, the relatively quicker way that water reenters into the aquifers is through human injection and irrigation (Vandenbohede et al., 2009). With this regard, the groundwater decreases with high fluctuations suggest a human intervention of the recharge-discharge system that speeds up the interaction between surface water and groundwater.

At the provincial scale, we are more confident with the results in those provinces whose administrative area is mostly within the YRB (Fig. 5a). Considering the limited points in Sichuan Province within the boundary of the YRB, the continuous decrease of groundwater storage in Sichuan doesn't necessarily mean that groundwater resource in Sichuan is extensively decreasing. It may be because the changed distribution of groundwater resource moving from north to south in Sichuan where we don't have data to present. However, for Ningxiahui, Shaanxi, and Shanxi, which are mostly covered by the YRB, the result of significant groundwater declines after 2010 indicates that regional recharges in these provinces have difficulty in effectively compensating the groundwater discharge in the regional system. That is to say, the groundwater "account" is in debt.

This groundwater debt may result from decreases in recharge, increases in discharge, or both. Decreases in recharge may be related to reduced precipitation and surface sealing from urbanization processes (Yu et al., 2003). Increases in discharge include withdrawals of groundwater for human use and increased evapotranspiration due to warming climate (Wegehenkel and Kersebaum, 2009). Therefore, both human and natural factors may lead to the same result of groundwater depletion. The Chinese Ministry Water Report confirmed that an extensive drought happened in 2010 in the North of China (Yellow River Conservancy Commission of MWR, 2010; Duan et al., 2011), which may have contributed to the decreasing trend in groundwater for nearly all provinces. Zhen and Routray (2002) found groundwater overextractions in Shandong province since the 1980s had led to well decline, land subsidence and compacted soil perceived by farmers. Meijer et al. (2006) also indicate that, by lining the canal with concrete material, the agricultural practices may reduce the groundwater recharge by approximately 50% in the irrigated areas. Rodell et al. (2018) suggested the increasing "human footprint" on the change of freshwater accessibility around the world. But they also noted that the temporal variabilities of freshwater reserve are mainly caused by inter-annual climate variabilities. For Qinghai province, the only province with increasing groundwater storage, Yang et al. (2003) detected an increase of precipitation and glacier melting there, which would increase recharge (Lutz et al., 2014). Clearer understanding on the interaction of human and natural factors and their synergistic effects on groundwater recharge-discharge balance remain to be explored in future studies.

Because the provinces located in the same geographical unit showed general consistency on spatio-temporal dynamics of groundwater, we believe it is meaningful to examine the groundwater situation in the reach level. Indeed, the spatial differences in groundwater storage among reaches within the YRB and temporal differences of groundwater time series in each reach are illuminating. Three reaches in the YRB showed quite unique features in the study period. The upper reach had relatively minor signs of groundwater decreases. This may partially result from the glacier melting and increased precipitation in the source region, which counteracts the groundwater decreases in the lower part of the upper reach (e.g. Ningxia and Neimenggu). The lower reach was relatively vulnerable, with both extreme high and low groundwater changes. This implies a more vulnerable ecosystem, thus posing more risks for human life. Middle reach acted as a transition with relatively smaller decreases than lower reach and larger decreases than the upper

reach.

These differences may be the result of biophysical differences among reaches, but they may also be driven by differences in population size, economic prosperity, and urbanization (e.g. surface sealing from construction and infrastructure development) (Feng et al., 2012). For example, in the upper reach, smaller population size may lead to reduced demand for groundwater, and thus showed relatively mild change (Feng et al., 2012). In the middle reach, human exploitation and environmental degradation have contributed to the changing climate over the past 50 years (Yang et al., 2004; Alter et al., 2017), leaving peoples with water crisis (Fu et al., 2004). Nevertheless, the population remains dependent on agriculture for economic development. With little surface water, this reach may be depleting groundwater to meet needs for irrigation (Yang et al., 2004). Higher rates of erosion in the middle reach has led to higher river bed in the lower reach. This may lead to a relatively high recharge level for aquifers in the lower reach. When groundwater is extracted, the water level will return more quickly because of the high pressure thus leading to more abrupt changes of groundwater storage. At the same time, high population density with high demand for water in the lower reach leads to more excessive use of groundwater, which may be the main reason of the significant decreases in this region (Anderson et al., 2013).

Most interestingly, we found the potential hysteresis of the groundwater changes from upstream to downstream. This hysteresis suggests that aquifers are also connected between reaches, so the signs of groundwater decreases in the upper and the middle reaches may be an earlier warning for the amplified groundwater decline in the lower reach. Currently, the emergence of extreme groundwater decreases (< -10 cm) in the middle reaches in 2015 and 2016 along with the increase of the months with extreme groundwater decreases in the lower reach has demonstrated this possible connection.

Apart from understanding the connection and pattern of aquifers through reach level, the cluster and outlier analysis further provides information on implications for management. Despite that the pixel-based analysis may be less reliable in explaining the spatial variabilities and its potential causes, we gave a try to at least give an example of how the analysis of its kind could provide information to decision-making. First, both the spatially shifted pattern of the hotspots and temporal

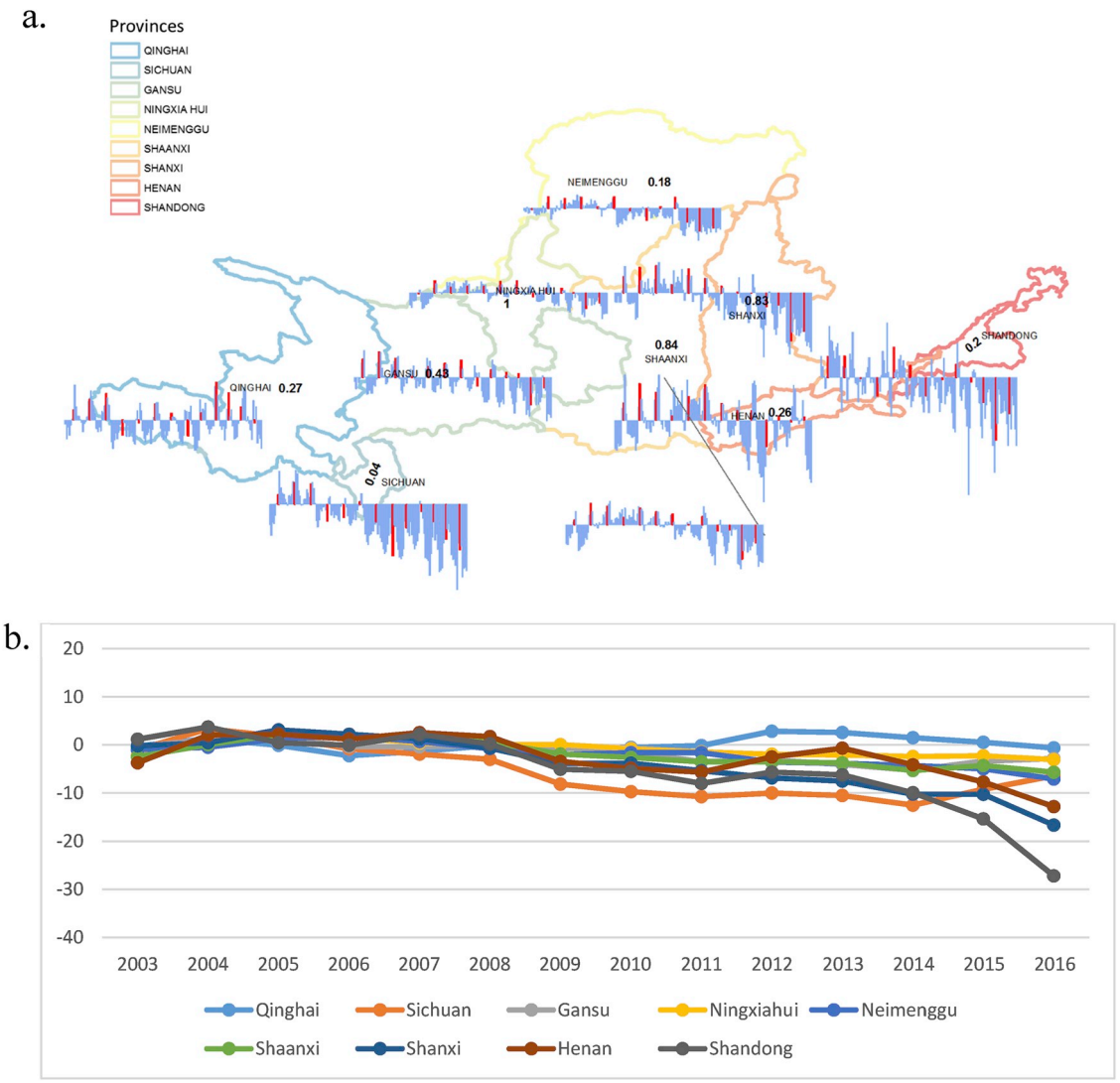

Fig. 5. Annual and monthly groundwater storage changes in the nine provinces (unit: cm). a) The monthly time series of the nine provinces in the YRB. To distinguish every year, all the bars in January are highlighted in red. The number in each color-outlined polygon represents the percentage of delineated area among the total area of each province. E.g. The "1" in the polygon of Ningxia means 100% area of Ningxia is within the YRB. b) The respective annual averaged groundwater storage changes compared with 2004–2009 baseline values in the nine provinces. The monthly groundwater storage changes compared with 2004–2009 baseline values for c) three provinces in the west (Qinghai, Sichuan, and Gansu), d) three provinces in the middle (Neimenggu, Ningxia Hui, and Shaanxi) and e) three provinces in the east (Shanxi, Henan, and Shandong). (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

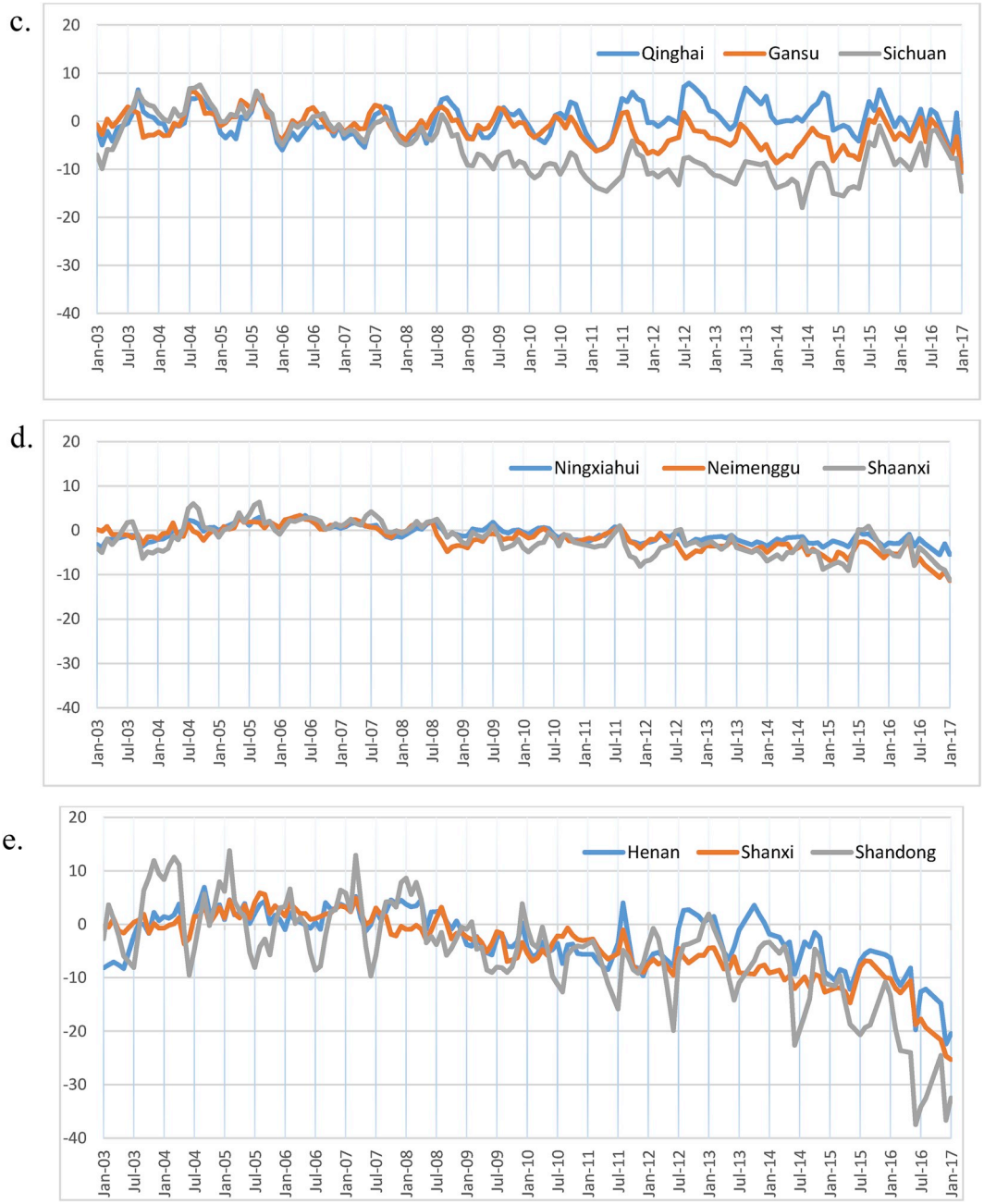

Fig. 5. (*continued*)

emergence of continuous decreases in all the reaches since 2010 suggest a different recharge-discharge environment for aquifers in the YRB after 2010. Second, the hotspots of groundwater decline changing from west (source region) to southeast (lower reach) may indicate that the human intervention become dominant in changing the recharge-discharge system. Also, the exceptional years that are inconsistent with general changes require further attentions. For example, in 2003 and 2004, the patterns were different from the following five years. Coincidentally, the temperature of the source region jumped from below zero to above zero in these two years (Du and Ma, 2016), which led to the increased glacier melting. This increase in glacier melting may be a probable cause of the increases of groundwater recharge in these two years. It can also be demonstrated by the increase of runoff in the Yellow River in 2003 and 2004 from the "*Water Resources Annual of the Yellow River*". Another exceptional year is 2011. In 2011, the central government has put forward a series of water regulation policies which may temporarily restrict the excessive groundwater use. However, the following years witnessed a returning sign of the groundwater depletion which implies that human intervention by management may pale in comparison with a long-term damage on the environment.

Admittedly, current spatial resolution of the GRACE data and GLDAS is still far from satisfactory to discuss groundwater situation in local scale. On one hand, current GRACE is still questionable in the interpretation in pixel scale. So the regions consisting of limited pixels (e.g. lower reach) may present more uncertainties induced by leakage errors. The total error (including both measurement and leakage errors) of the GRACE dataset in the YRB is about 3.12 cm in average and is especially evident in the southeast around the lower reach (Fig. 7). Newly released mascon data (Save et al., 2016) may provide a better solution to reduce these errors. However, readers should take caution on its actual resolution of the information. The native resolution of the GRACE mascon solution is actually 3°, the size of a single mascon.

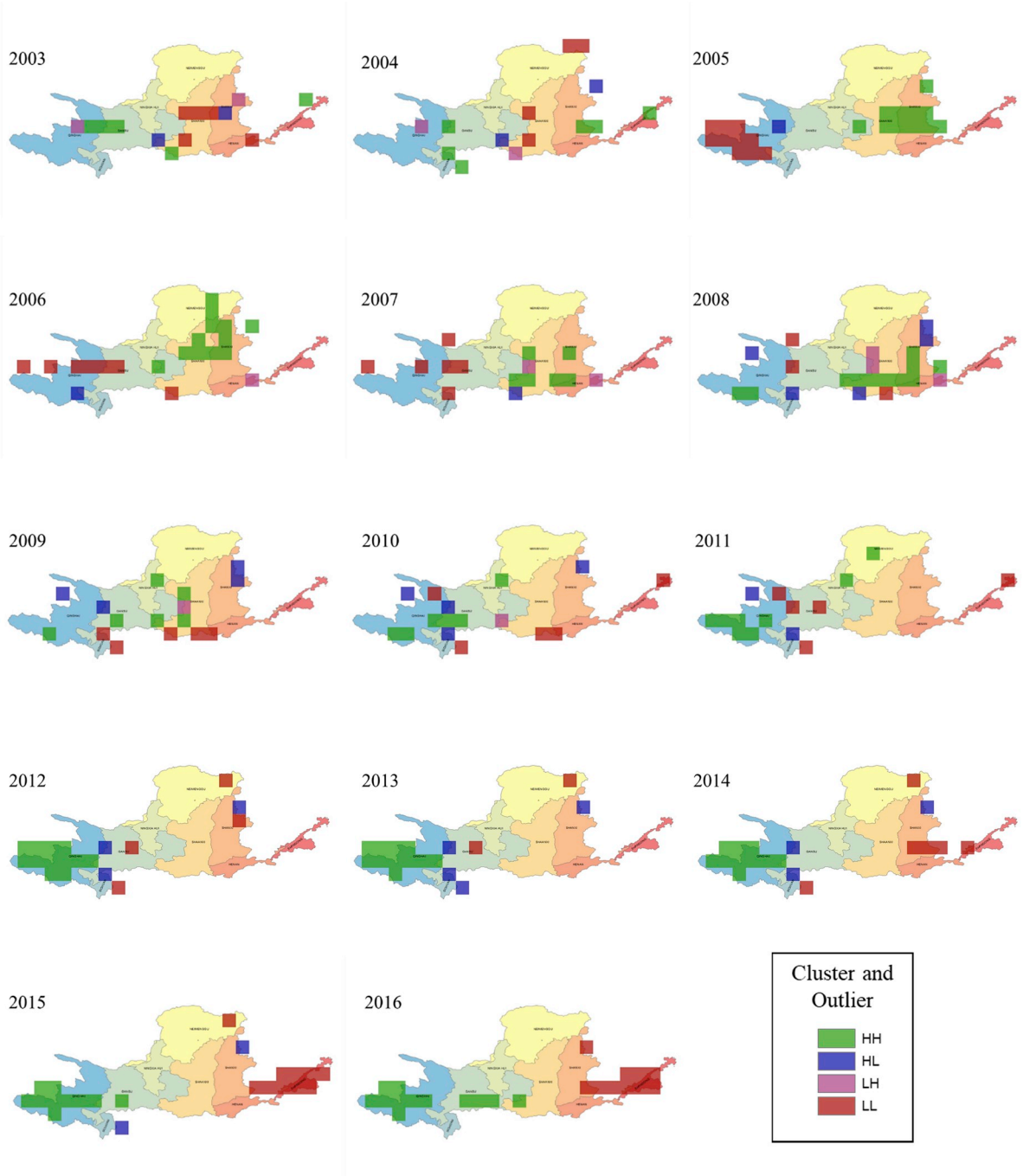

Fig. 6. Annual clusters in the YRB from 2003 to 2016. The color polygons constitute the provincial map of the YRB following the color legend in Fig. 2b. The cluster and outlier points are represented by pixels covering the provincial map. HH (green) is a statistically (95% confidence level) significant cluster of groundwater increases and LL (red) represents a statistically significant cluster of groundwater decreases. HL represents the abnormal point where the groundwater storage is higher than surrounding area, while LH represents the abnormal point with a lower groundwater storage than surroundings. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Therefore, it is not suitable for analysis in grid point scale. On the other hand, the surface water component of GLDAS used in this study doesn't include the separate water component like lakes or reservoirs. But since lakes and reservoirs are sparsely scattered in the YRB (Yang and Lu, 2014) and groundwater is commonly viewed as spatially continuous across the region of interest (Rodell et al., 2007), the investigation of the overall spatio-temporal trend of the groundwater in the YRB would effectively eliminate the scattered or abrupt changes caused by the separate surface water components. Still, human factors like artificial dam constructions may change the temporal dynamics of the river runoff thus inducing a nonnegligible inaccuracy for the groundwater measurement (Liu et al., 2012). Future studies are required to incorporate other Land Surface Models (Long et al., 2015) to improve the estimation.

Despite of the uncertainties mentioned above, it should be noted that a consistent criterion for discussing groundwater variance is necessary to understand the connections of groundwater changes between regions, thus helping to resolve the debate on trans-boundary water resource and to diminish the potential of war for water. This study provides fundamental support for further studies about socio-ecological

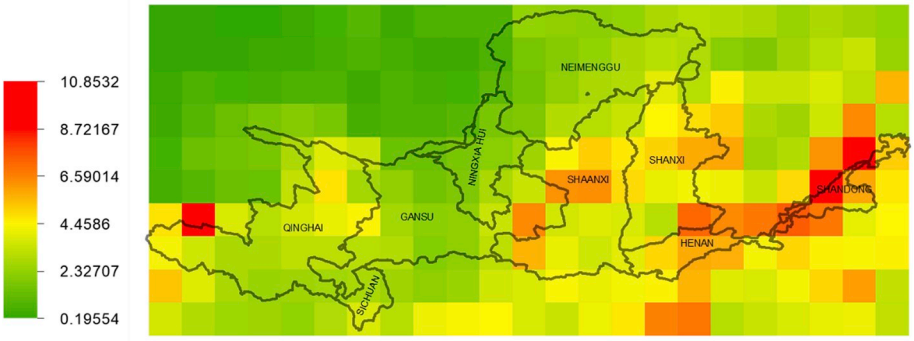

Fig. 7. Error estimate of the GRACE datasets in the YRB-covering rectangle region (unit: cm). Green represents the lower values while the red represents the higher levels of the errors. Readers should take caution on the interpretations of the results in the red pixels. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

factors of groundwater changes. Future studies should focus on the combined effects of human and nature on groundwater decreases, which may further empower the managers to incorporate groundwater use plan into overall scheme of sustainable water management.

5. Conclusions

We quantified groundwater changes in the Yellow River Basin of China and conducted spatio-temporal analysis to quantify the changes of groundwater storage at multiple scales. Overall, there was a decreasing trend ($R^2 = 0.57$) in groundwater storage during the last 14 years over the whole basin. After 2010, the YRB exhibited stronger fluctuations and were usually coupled with larger decreases in groundwater storage. At the same time, the groundwater storage changes were both spatially and temporally heterogeneous. Groundwater storage declines generally got more severe from west to east (e.g. An averaged groundwater decrease of −3.6, −9.1 and −25.8 cm respectively for the upper, middle and lower reach in December 2016), and from past to recent (e.g. decreasing slope changed from −0.0137 cm/month in 2003-2009 to −0.0684 cm/month in 2010-2016 at basin scale). The hotspot analysis reemphasized the heterogeneity in groundwater decline across the basin and through the time. From the management perspective, the result of the general decline in the YRB from 2003 to 2016, especially after 2010, implies that we are not on the right track in protecting groundwater. The hotspots of the groundwater decline shifted from the source region to the lower reach indicating that “human footprint” may become dominant in affecting groundwater changes. At the same time, our studies across different spatial levels indicate that geographical conditions may also play a role in determining the groundwater patterns in the YRB and a one-size-fits-all management is unlikely to be effective. This information demonstrates the need for cooperative water management across neighboring administrative regions while simultaneously designing management practices that are relevant to the local situation. Overall, our studies provide clearer message to water managers about the necessity and the direction to consider groundwater into management scheme so as to ensure a sustainable water use for future.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2019.01.016.

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